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Identifying Suitable Ballast Settlement Models and Types of Ballast Breakage from Field Representative Ballast Box Tests

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Abstract

The simulation of field conditions on ballast in the laboratory aids the identification of the overall response and performance of the ballast layer and the resulting impact on track structure deterioration. The permanent deformation of ballast under cyclic loading often accounts for the largest portion of track settlement of all layers that constitute the track structure. Hence, utilizing best-fit ballast settlement models aids in identifying the need for track maintenance interventions and adequate planning. Furthermore, the use of high-quality ballast is essential to maintain geometric stability and to enhance the durability of ballast particles on heavy haul tracks. In addition, it is important to ensure adequate compaction and confinement of ballast on railway lines. This will limit the occurrence of various types of ballast breakage which affect the integrity of the track structure. The objective of this paper is to describe best-fit ballast models that can predict the gradual deformation of ballast as well as different types of ballast breakage under field loading and boundary conditions. Ballast deformation is accurately predicted by existing best-fit ballast settlement models defined by different levels of lateral confinement. Ballast breakage results reveal that attrition of asperities and corner breakage are the foremost types of breakage, where an increase in lateral confinement of the ballast layer could limit excessive ballast breakage to acceptable levels. From the findings of this research, ballast settlement can be accurately predicted for regular track geometry monitoring and maintenance using best-fit settlement models for any level of lateral confinement. Furthermore, high quality ballast material utilized on railway lines could extend track maintenance intervals.

Keywords: box testing, field loading, lateral confinement, ballast settlement, ballast breakage, ballast settlement models, track monitoring, track maintenance.

1 Introduction

The objective of this research is to predict the gradual deformation of ballast by describing best-fit ballast models defined by different levels of lateral confinement for regular track geometry monitoring and maintenance. Furthermore, the aim of this work is to identify the types of ballast breakage under field loading and boundary conditions. This can provide better insight into the importance of adequate ballast compaction, lateral confinement and the provision of high-quality ballast to extend track maintenance intervals.

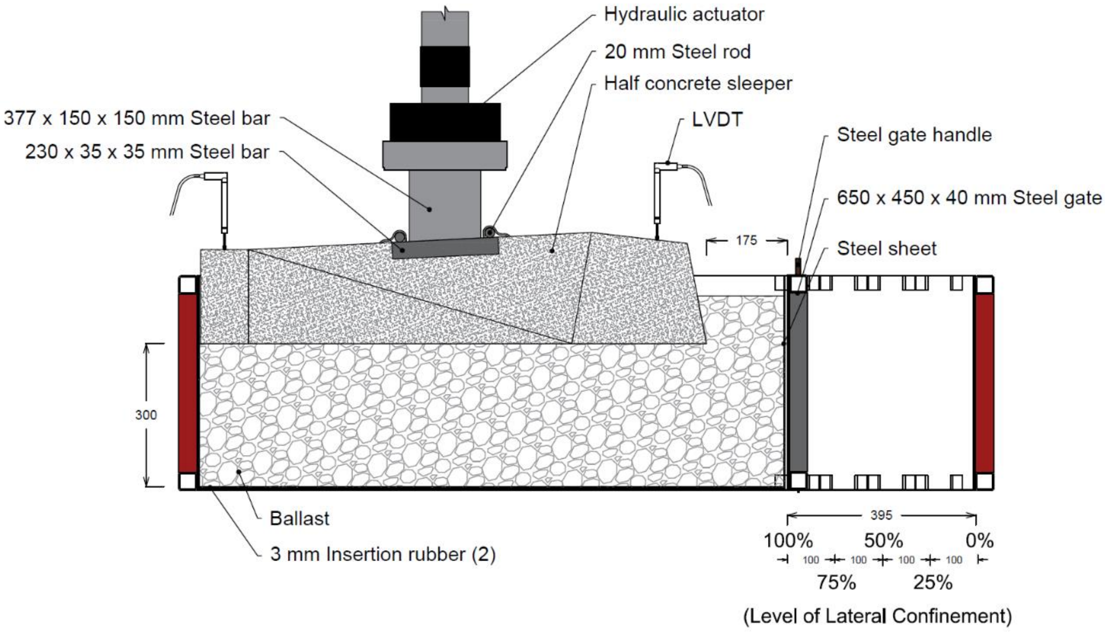
The ability of ballast to retain stable track geometry depends mainly on material quality, physical state and load magnitude. Based on numerous studies, the relationship between the number of load applications and settlement of ballast has been found to be non-linear. It is observed that most existing ballast models are a function of number of cycles [1 - 4]. Other existing ballast models based on the number of load cycles also consider variables such as load amplitude [5], axle load, rail section, sleeper spacing and track and foundation stiffness [6], stress and modulus of subgrade [4].

This work seeks to identify a suitable ballast settlement model(s) that considers the changes in lateral confinement under field loading conditions. McDowell [7] stated factors that govern the survival probability of a particle in an aggregate subjected to a one-dimensional compressive load. These factors are applied macroscopic (external) stresses, size of the particle and coordination number (i.e. number of contacts with neighbouring particles). Lade [8] summarized the most widely used particle breakage indices as proposed by others [9 - 14]. Some indices proposed above are based on changes in a single particle size, while others are based on changes in overall grain-size distribution.

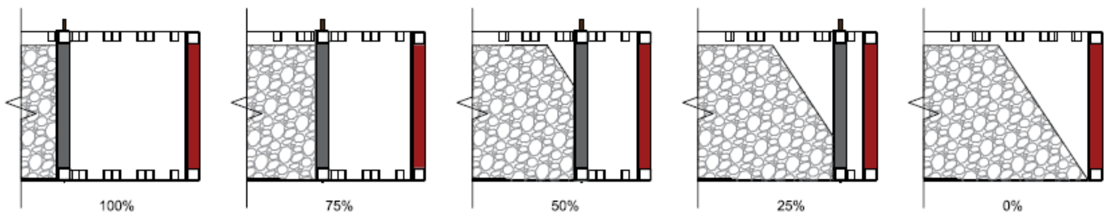
The influence of confining pressure on the behaviour of ballast was divided into three zones following a series of triaxial tests [10, 11]. These zones are (I) Dilatant Unstable Degradation Zone (DUDZ) where most ballast degradation is due to breakage of angular corners and minimal splitting of particles; (II) Optimum Degradation Zone (ODZ) with attrition of asperities due to an increase in the coordination number, and (III) Compressive Stable Degradation Zone (CSDZ) where particle splitting due to microcracks, particle flaws, and fatigue are common types of ballast breakage.

2 Methods

The laboratory tests involved a full-scale box test with an adjustable length to investigate the effect of lateral confinement on ballast settlement and breakage. The steel box, 1 630 mm long, 650 mm wide and 450 mm deep, was built to represent a half sleeper bay of a typical railway track, considering track longitudinal symmetry and the minimum requirements of the ballast layer for a 1 065 mm gauge South African Coal Line [15]. A schematic illustration of the materials, measuring devices and equipment and their locations, are shown in Figure 1.



(a)



(b)

Figure 1: Schematic (cross section (a) and confinement (b)) illustration of experimental materials and instrumentation.

The experimental procedures for this setup was employed to quantify the breakage of ballast and to measure the settlement of the ballast layer while varying the levels of lateral confinement (which is expressed as the percentage of the ballast shoulder that is being confined in the lateral direction in the ballast box). The large steel box was designed to accommodate five levels of lateral confinement, namely 100 % (fully confined), 75 %, 50 %, 25 % and 0 % (full ballast shoulder) (Figure 1).

Fresh quartzite ballast samples were used for each level of lateral confinement. Ballast breakage was assessed at two locations in the ballast layer: at approximately 10 mm and at 300 mm from the bottom of the sleeper. 10 kg of ballast were painted sparingly to study the surface friction of the ballast. The painted ballast was placed unconfined in the region below the sleeper loaded area, with the painted ballast at

10 mm overlaid with normal ballast to achieve ballast breakage due to interparticle contact forces. Each box sample was compacted in three layers following the rodding procedure outlined in the ASTM C29 standard [16]. Further compaction was conducted by applying 5 000 and 20 000 cyclic loads of 45 kN and 90 kN respectively, at 10 Hz using the MTS hydraulic actuator.

A suitable loading pattern which was developed to represent field loading conditions (presented in the first part of this work) was applied at 10 Hz with a load range from 2.5 kN to 91 kN. 325 000 load cycles were applied to each ballast box sample. Sieve analyses were conducted on the painted ballast at 100 mm and 300 mm at the beginning and end of the cyclic loading.

3 Results

Published ballast settlement (S_N) and strain (ε_N) models from previous research were compared with the laboratory ballast settlement and strain data respectively as a function of number of cycles (N) and other related parameters. The method of least squares was used to best-fit these models to the experimental data.

From the plots of permanent settlement, S_N, shown in Figure 2 for 100 % lateral confinement, the following were observed:

- Settlement deformation models established by Selig & Waters [1] and Sato [17], which are power functions, produced similar settlement trends as the test data settlement with final settlements of 27.3 and 29 mm respectively in comparison to the test settlement data of 27.6 mm after 325 000 cycles.
- The Log linear models of Stewart & Selig [18] and Neidhart [19] under-predicted the settlement.
- The settlement model of Thom & Oakley [4] is a logarithmic function of solely the number of cycles. Hence, it provides a poor prediction of the ballast settlement during the test.

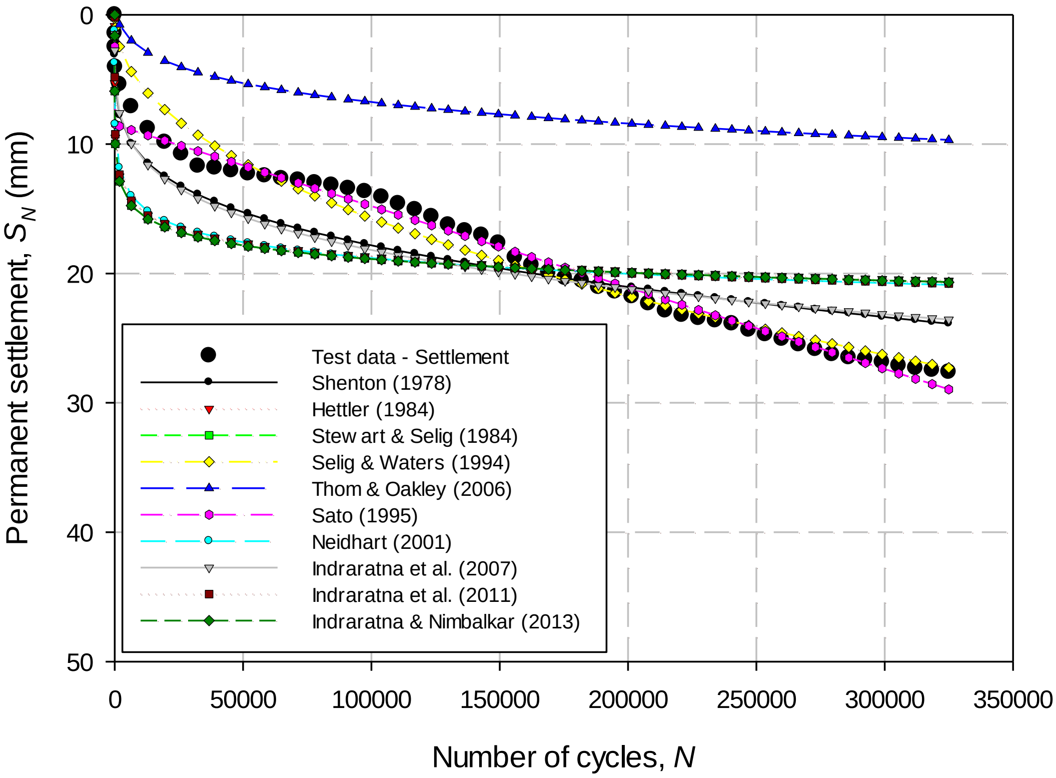


Figure 2: Ballast permanent settlement models fitted to the settlement test data of 100 % confinement.

From the plots of permanent strain, ε_N, shown in Figure 3, the following were observed:

- Strain deformation models established by the Selig & Waters [1] power model provides a good prediction of the axial strain deformation at 100 % confinement.
- Log linear models of ORE [20] and Shenton [21] under-predict the final axial strain of the test data.
- The model by Alva-Hurtado & Selig [3] provides a poor estimate of axial strain deformation.

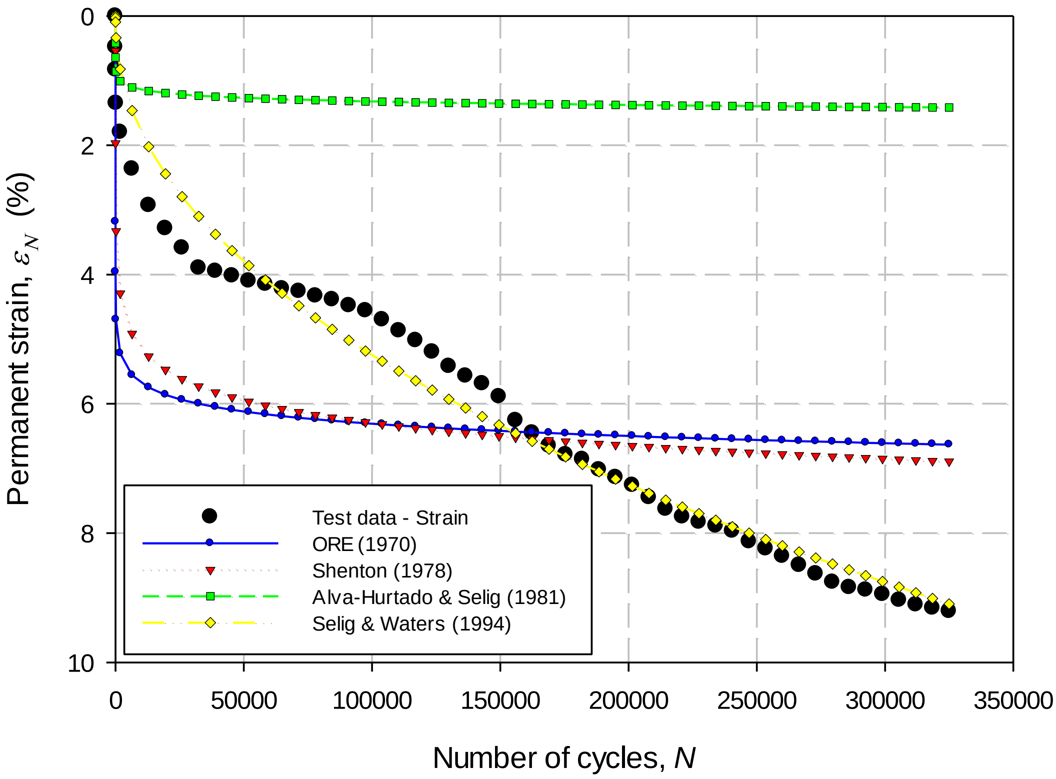


Figure 3: Ballast permanent strain models fitted to the strain test data of 100 % confinement.

In Table 1, the permanent deformation models with high R^2-values across all levels of lateral confinement include Shenton [6], Selig & Waters [1] and Sato [17].

Model reference	Coefficient of determination, R^2 for each lateral confinement level				
	100%	75%	50%	25%	0%
Shenton (1984) [6] – S_N	0.82	0.95	0.91	0.99	0.73
Hettler (1984) [5]	0.48	0.62	0.58	0.74	0.40
Stewart & Selig (1984) [18]	0.46	0.61	0.51	0.73	0.38
Selig & Waters (1994) [1] - S_N	0.96	0.99	0.99	0.997	0.96
Thom & Oakley (2006) [4]	-2.53	-7.53	-7.07	-11.8	-3.91
Sato (1995) [17]	0.99	0.97	0.99	0.98	0.98
Neidhart (2001) [19]	0.51	0.66	0.65	0.77	0.44
Indraratna et al. (2007) [22]	0.79	0.90	0.71	0.996	0.64
Indraratna et al. (2011) [23]	0.49	0.63	0.58	0.75	0.41
Indraratna & Nimblkar (2013) [24]	0.46	0.61	0.51	0.73	0.38
ORE (1970) [20]	0.34	-0.15	-0.92	-2.36	-0.88
Shenton (1978) [21] - ε_N	0.46	0.60	0.51	0.73	0.38
Alva-Hurtado & Selig (1981) [3]	-5.03	-6.71	-1.27	-12	-2.46
Selig & Waters (1994) [1] - ε_N	0.96	0.99	0.99	0.997	0.96

Table 1: Coefficient of determination, R^2 values for permanent deformation models.

Figure 4 (a) shows corner breakage after cyclic loading at 100 % lateral confinement. Attrition of asperities (Figure 4 (d)) and particle splitting are the foremost types of breakage across all levels of confinement. Figure 4 (b, c, and e) show particle splitting observed from a full ballast shoulder profile (0 % confinement), 75 % and 25% lateral confinement tests, respectively. Figure 4 (f) and (g) show particle breakage along weak planes (such as micro cracks and flaws) and particle splitting, respectively. Fracture strength of a ballast particle is a major governing factor enhancing ballast breakage. Therefore, procuring high quality ballast for heavy haul railway lines to ensure limited degradation of the ballast layer and track structure is essential.

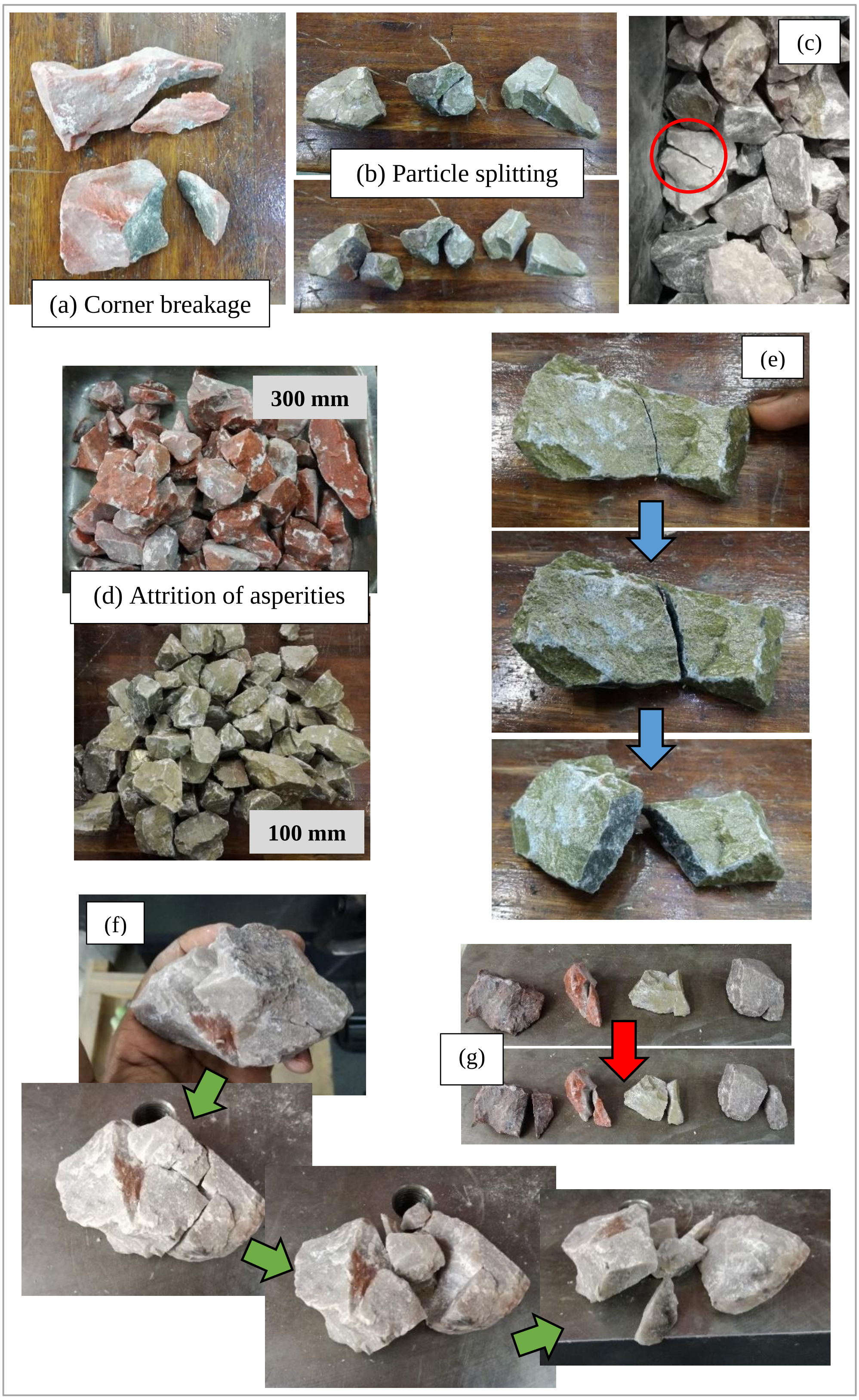


Figure 4: Types of ballast breakage

4 Conclusions and Contributions

From this study, it can be concluded that decreasing the level of lateral confinement causes an increase in the permanent strain of the ballast layer. The ballast permanent deformation models of Selig & Waters [1] (power function) and Sato [17] accurately predicted the settlement trends of the test data. The variables of the power function also considered the levels of lateral confinement. These models can be implemented in the monitoring of ballast settlement and planning for maintenance interventions. Deformation models based on log-normal and number of cycles do not consider the levels of lateral confinement. Although the overall ballast sample size may not be statistically significant to assign types of ballast breakage to each lateral confinement, common types of ballast breakage identified include attrition of asperities, corner breakage, particle splitting and particle breakage along weak planes. Practical applications could be implemented to increase the confinement level and limit the permanent settlement and ballast deterioration of ballasted tracks such as geosynthetic ballast layer reinforcement placed at the bottom of the ballast layer, placing intermittent lateral restraints at various track sections and increasing the volume of ballast at the ballast shoulder by decreasing the slope of the ballast shoulder [10].

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References

[1] E.T. Selig, J.M. Waters, “Track geotechnology and substructure management”, Thomas Telford, London, 1994.

[2] D. Li, J. Hyslip, T.R. Sussmann, & S.M. Chrismer, (Eds) “Railway Geotechnics”, Boca Raton, FL: CRC Press/Spon Press, 2015.

[3] J.E. Alva-Hurtado, E.T. Selig, “Permanent strain behaviour of railroad ballast”, Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, Vol 1, 543 – 546, 1981.

[4] N.H. Thom, J. Oakley, “Predicting Differential Settlement in a Railway Trackbed”, Railway Foundations, Birmingham, UK, 2006.

[5] A. Hettler, “Bleibende Setzungen des Schotteroberbaus », ETR Eisenbahntechnische Rundschau 33, Vol. 11, 847-853, 1984.

[6] M.J. Shenton, “Ballast Deformation and Track Deterioration”, Track Technology, London: Thomas Telford Ltd, 1984.

[7] G. McDowell, M. Bolton, D. Robertson, “The fractal crushing of granular materials”, Journal of the Mechanics and Physics of Solids 44(12), 2079–2101, 1996.

[8] P.V. Lade, J.A. Yamamuro, P.A. Bopp, “Significance of particle crushing in granular materials”, Journal of Geotechnical Engineering, ASCE, Vol. 122, No. 4, pp. 309–316, 1996.

[9] R.J. Marsal, “Large scale testing of rockfill materials”, Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM2, pp. 27-43, 1967.

[10] B. Indraratna, J. Lackenby, D. Christie, “Effect of Confining Pressure on the Degradation of Ballast under Cyclic Loading”, Geotechnique, Institution of Civil Engineers, UK, Vol. 55, No. 4, pp. 325-328, 2005.

[11] J. Lackenby, B. Indraratna, G. McDowel, “The Role of Confining Pressure on Cyclic Triaxial Behaviour of Ballast”, Geotechnique, Institution of Civil Engineers, UK Vol. 57, No. 6, pp. 527-536, 2007.

[12] K.L. Lee, I. Farhoomand, “Compressibility and crushing of granular soil in anisotropic triaxial compression”, Canadian Geotechnical Journal, Vol. 4, No. 1, pp.69-86, 1967.

[13] B.O. Hardin, “Crushing of soil particles”, Journal of Geotechnical Engineering, ASCE, Vol. 111, No. 10, 1177–1192, 1985.

[14] N. Miura, S. O-hara, “Particle crushing of decomposed granite soil under shear stresses”, Soils and Foundations, Vol. 19, No. 3, pp. 1-14, 1979.

[15] TFR (Transnet Freight Rail) S406, “Specification for the Supply of Stone”, Johannesburg: TFR, 1998.

[16] ASTM (American Society of Testing and Materials) C29/C29M-17a “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate”, West Conshohocken, PA: ASTM International, 2017.

[17] Y. Sato, “Japanese studies on deterioration of ballasted track”, Vehicle System Dynamics, 24:(Suppl.), pp. 197–208, 1995.

[18] H.E. Stewart, E.T. Selig, “Correlation of Concrete Tie Track Performance in Revenue Service and at the Facility for Accelerated Service Testing”, Prediction and Evaluation of Track Settlement. Washington, DC: U.S. Department of Transportation Federal Railroad Administration, 1984.

[19] T. Neidhart, “True-to-scale in situ tests determining dynamic performance of earthworks under high speed train loading”, Proc., Geotechnics for Roads, Rail Tracks and Earth Structures, Vol. ETC11, ISSMGE, Rotterdam, Netherlands, 213–223, 2001.

[20] Office of Research and Experiments (ORE), Stresses in Rail, Question D71, “Stresses in the rails, the ballast and the formation resulting from traffic loads”, Report No. D71/RP1/E, Int. Union of Railways, Utrecht, Netherlands, 1965.

[21] M.J. Shenton, “Deformation of Railway Ballast under Repeated Loading Condition”, In: KERR, A. D., ed. Railroad Track Mechanics and Technology: Proceeding of a Symposium, Princeton University, 1978.

[22] B. Indraratna, M.A. Shahin, W. Salim, “Stabilising granular media and formation soil using geosynthetics with special reference to railway engineering”. Ground Improvement, 11(1), 27–44, 2007.

[23] B. Indraratna, W. Salim, C. Rujikiatkamjorn, “Advanced rail geotechnology–ballasted track”, CRC press, 2011.

[24] B. Indraratna, S. Nimbalkar, “Stress-strain degradation response of railway ballast stabilized with geosynthetics”, Journal of Geotechnical and Geoenvironmental Engineering, 139 (5), 684-700, 2013.